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14. ABSTRACT
This document serves as an interim report for the HAPsMRT. A prototype surgical robot from the University of Washington was deployed in an extreme environment near Simi Valley, CA. The robot controller (master) and robot (slave) were separated by approximately 100 feet. These were connected wirelessly using AeroVironment's Unmanned Airborne Vehicle (UAV). Using this system, University of Cincinnati surgeons were able to manipulate the end effectors. This demonstrated that a surgical robot could be deployed in an extreme environment and controlled by a surgeon who was remotely located from the robot using a wireless communication system (UAV) normally used for military operations.

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INTRODUCTION

This report serves as an interim report for grant, entitled High Altitude Platforms (HAPs) for Mobile Robotic Telesurgery (MRT) (W81XWH-05-2-0080). It covers the initial activities performed during the year (September 2005 – September 2006) in a lead up to the efforts conducted in Simi Valley, CA in June 2006.

The primary objective of this project was to develop and validate a communication and robotic surgical system that would allow a remote surgeon to effectively operate on an injured soldier regardless of the soldier's location or environment. These experiments validated MRT through use of an unmanned aerial vehicle (UAV)-based communication system and a prototype next generation surgical robot. A set of experiments were conducted in an extreme environment – the high desert surrounding the AeroVironment facilities in Simi Valley, CA.

This effort was collaborative initiative between the University of Cincinnati (UC), the University of Washington (UW), AeroVironment, and HaiVision.

This work has provided an opportunity to conduct additional MRT research and development between UC and UW. This research is being worked out and will be conducted during the one year no cost extension.

BODY

Project Description

While advances in robotics and computing have resulted in robust surgical robots that are currently used in operating rooms across the world, similar advances in telecommunications and computing have permitted development of telemedicine, which has seen a global expansion. Surgical teleconsultation is effective in bringing surgical expertise to the previously isolated operating room. Similarly, teleconsultation could overcome the barriers of time and distance and interject expertise and order into the care of a soldier in the midst of the chaos of the battlefield. Prompt, definitive care from a distance could improve soldier survival as well as decrease the cost and risk of delivering medical care.

Remote robotic surgery, or telesurgery, has not been feasible primarily because the robotic systems were not robust enough and the necessary low latency broadband telecommunications connections were not widely available. Dr. Jacques Marescaux's original and our recent basic science and clinical telesurgical experience demonstrated the applicability of remote robotic telesurgery. This experience suggests that telesurgery could facilitate medical care by allowing a remote surgeon to operate effectively on a distant soldier. Prior experience demonstrated that shorter latency results in improved surgical performance.

During military conflict, reliable broadband terrestrial communications capabilities to support surgical services are not available. Therefore, telesurgery systems in remote terrestrial theaters of war will require wireless communication. The wireless system will have to provide a high bandwidth, low latency connection between the operating surgeon and the distant robotic system similar to terrestrial systems. In selection of a wireless system for use in telesurgical applications, communication latency is of primary importance.

Satellite communication latency is a function of orbital altitude or position of the satellite in space. There are three primary types of satellites routinely utilized for communication: Low Earth Orbit (LEO), Mid Earth Orbit (MEO), and Geostationary Earth Orbit (GEO). While GEO systems have enough bandwidth for use in robotic telesurgical systems, the communication latency precludes GEO system use. MEO satellites have a low enough latency and can transmit at acceptably high data rates if enough bandwidth is dedicated to the communications link. Unfortunately there are limited MEO satellites currently in operation, and tracking these assets requires additional equipment. MEO-based telesurgery will be possible only with further MEO satellite system development. While there are commercially available LEO systems with low communication latency, the bandwidth per link is too low for practical use in robotic telesurgery (approximately 30 Kilobits per second [Kbps]).

Based on the unavailability of a usable satellite communication system for MRT, we partnered with AeroVironment to use their UAV-based telecommunications system in this project. AeroVironment has developed multiple UAVs. They agreed to provide use of their Puma, a small UAV (SUAV) currently used in Iraq and Afghanistan, for these experiments.

This project used the U.S. Army-funded, next generation surgical robot prototype currently under development at UW. The MRT system consisted of the UAV-based communication system and the prototype next generation surgical robot. The system was validated in an extreme environment – the high desert in Simi Valley, CA.

To effectively implement this activity and sustain it as a strategic initiative, a consortium was established between the UC – Center for Surgical Innovation (CSI) and UW, Aerovironment, and HaiVision. This project brought together the necessary military, surgical, robotic and telecommunications partners to provide the eclectic, nascent technologies and expertise that will make mobile robotic telesurgical care of soldiers a reality.

Research Plan

The overall objectives of HAPsMRT included in the original proposal were:

1) Develop, deploy, and validate the MRT system via inanimate mobile telesurgery experiments in an extreme environment. These experiments were designed to evaluate surgeon performance using telesurgical technique. During these

experiments, a surgeon would operate from a Remote Command Center (RCC) connected to a robot within the distant Mobile Operating Room (MOR). The original intent was to conduct the tests at the Pacific Missile Range Facility in Hawaii. *Due to availability and schedule this experiment was performed in California.*

2) In the first stage of these experiments, the surgeon would operate from the RCC that was stationed at one location to the MOR located at a different site. The local communication link would be provided by a circling UAV drone. *The High Altitude Long Endurance (HALE) UAV Helios was unavailable secondary to a flight accident and therefore the SUAV Puma was used.*

3) In the second phase of these experiments, a surgeon would operate using a second RCC stationed at the UW in Seattle with the MOR remotely stationed at the distant site. The communications link connecting the Seattle surgeon to the remotely-located robot would be provided though use of a commercial Internet Protocol (IP) network to the existing downlink.

In these experiments, the surgeon would perform several simple surgical tasks with data to be analyzed after including the following attributes: (1) ease of the MRT, (2) difficulties of MRT in an extreme environment, (3) visualization provided by the allocated bandwidth, (4) impairment of performance imposed by latency and signal loss, and (5) feasibility of future MRT on the battlefield. Figure 1 illustrates the experimental setup in an extreme environment.

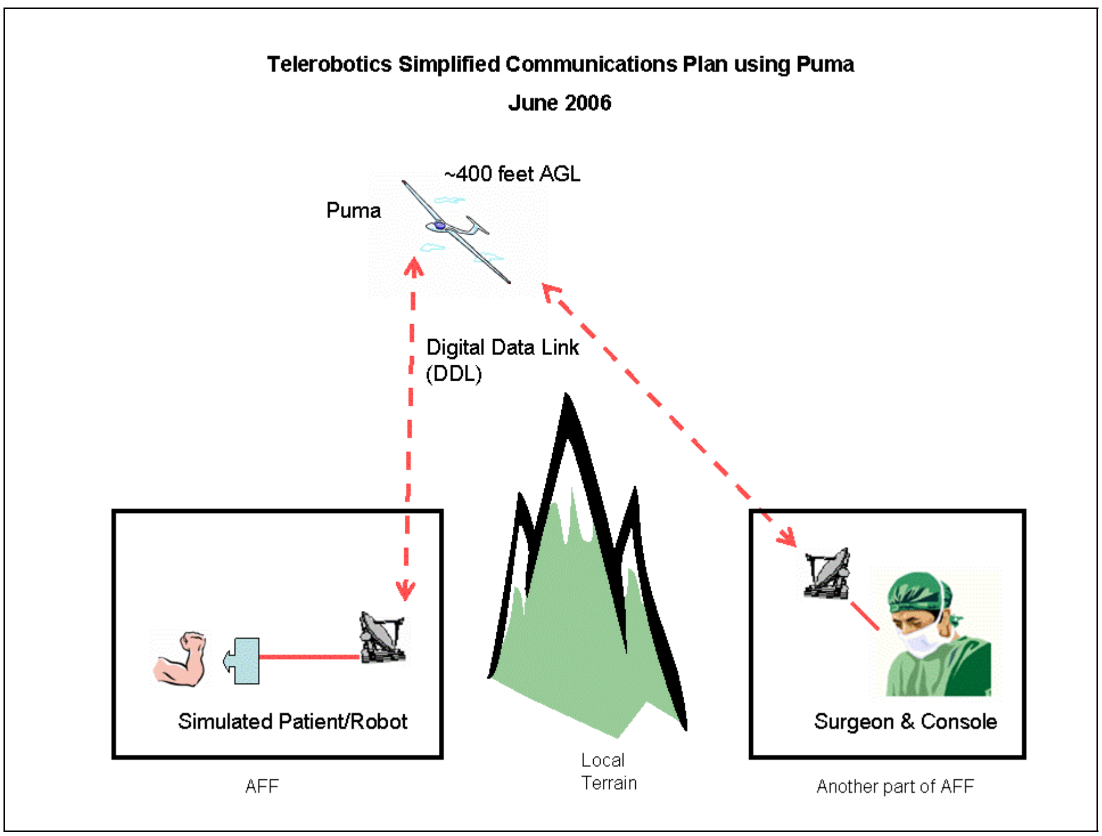


Figure 1. Experimental setup in Simi Valley, CA.

KEY RESEARCH ACCOMPLISHMENTS

Experimental Team

This research was conducted through the collaboration of several individuals representing UC, UW, Aerovironment, and HaiVision. Table 1 lists those individuals.

Table 1. HAPsMRT team members

Team Member Name	*Organization*
Timothy J. Broderick, MD	University of Cincinnati
Charles R. Doarn, MBA	University of Cincinnati
Brett M. Harnett, BS	University of Cincinnati
Lynn Huffman, MD	University of Cincinnati
Lance Boulet	HaiVision
Jos Cocquyt	AeroVironment
Ted Wierzbanowski	AeroVironment
Phil Tokomuro, Ph.D.	AeroVironment
Blake Hannaford, Ph.D.	University of Washington
Jacob Rosen, Ph.D.	University of Washington
Hawkeye King, M.S.	University of Washington
Mitch Lum, M.S.	University of Washington
Diana Friedmann, M.S.	University of Washington
Gina Donlin	University of Washington

Experimental Setup Overview

Once the prototype robotic system was assembled and benchmarked at the robotics laboratory at the UW in Seattle, WA, it was driven to southern California. The team gathered at AeroVironment's facilities in Simi Valley, CA on June 4, 2006. The robotic systems was assembled and tested inside the facilities to determine the amount of time it would take to assemble the unit from packaging through final assembly and operations. This system also included the integration of HaiVision's high performance Hai 500 MPEG 2 Compressor/Decompressor (CODEC).

AeroVironment provided use of one of their UAVs – Puma. The Puma is a small UAV that flies at altitudes below 15,000 feet mean sea level (MSL) and can provide line of sight communication up to a distance of 12 km with low gain antennas and 20 km with higher gain antennas. (See photo inset) The system was integrated and flight tests were performed. UAV-based low latency broadband digital communication was established; problems were identified, and subsequently resolved during experimental deployment in the desert environment.

Once the system was set up, the surgeon(s) would manipulate the robotic system wirelessly, where surgeon and robot were separated by two distances. First, the distance would be measured in feet (~100 feet) - locale and second, in miles, between Simi Valley and Seattle, WA.

During the week of experimentation, the system was deployed in a rural, arid area in the high desert of Simi Valley, referred to as the flying field. There was no electrical power, water or shade. Two tents were set up and separated by a distance of approximately 100 feet. Initially, close proximity of the two tents facilitated troubleshooting of the prototype mobile robotic surgical system. (See inset photos). Electrical power was provided by two portable gasoline-powered generators. The photo with the flag was the location of the robot. The second tent was the location of the surgeon controllers.

This set up was performed at three different sites. Set up time was measured in hours at the beginning of the week. By the week's end, the time was approximately 30 minutes.

The master controllers were the SensAble Phantom (http://www.sensable.com/haptic-phantom-omni.htm). These devices permitted wireless manipulation of the end effectors, which were located on the robotic arms, approximately 100 feet away. Despite close proximity of the two tents, signal transmission from master to SUAV to slave was approximately 5 km. Video images were transmitted through use of HaiVision's CODEC.

This experimental configuration provided an opportunity to evaluate the various communication modalities, performance of the surgeon, and the impact of the extreme environment.

Communication Challenges

The Puma-based communication system provided by AeroVironment was not fully function upon arrival of the team. Prior to the team's arrival in Simi Valley, the AeroVironment engineers had successfully tested the prototype communication link independent of the Puma platform. However, once the DDL was this integrated into the aircraft, the unit ceased to operate. This unforeseen event prompted a real-time workaround.

The workaround was to implement a standard Wi-Fi (802.11g) wireless network. While the UW continued to diagnose the problem, the other members of the team went to a local electronics store and purchased wireless access points, receivers, routers, switches and other ancillary devices (AeroVironment absorbed the cost of approximately $1,000).

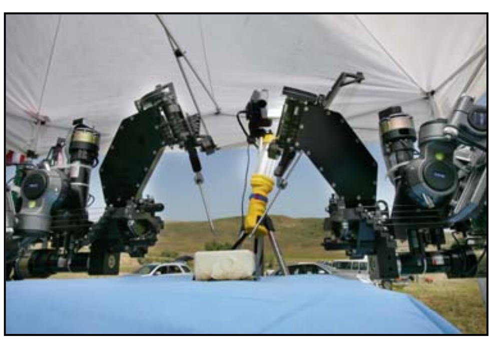
One of the challenges was to construct a self-contained wireless local area network (WLAN) where the endpoints connected to the access point (which would be the aircraft) and not directly to each other. For the next two days a private WLAN was built and tested. This 802.11g wireless system allowed wireless remote manipulation of the surgical robot while on the UAV was on the ground, but it was more challenging once the system was airborne.

On Wednesday the UAV-based Wi-Fi communication system was deployed in the field. The Puma was outfitted with the access point, launched and was flown in a small circle above the experimental site in the field. Directional antennas at the downlink points were used to acquire a signal. (see photo inset).

A series of tests were conducted to determine the optimal flight characteristics, altitude, and distance to maximize network connectivity. The Wi-Fi's coverage was inconsistent. Various antennae configurations were tried with little effect. Direction and flight attitude resulted in inconsistent radio communications. The aircraft's engine possibly added interference with the WiFi signal, evidenced by improved throughput on the descent and decreased engine throttling. However, additional testing suggested the intermittent loss of signal during flight was likely related to the directional nature of the router antennae on the UAV.

On Thursday AeroVironment finally resolved the issues with the DDL obviating the need for the backup plan of the WiFi. The original system became operational and a series of successful tests were accomplished as outlined below.

<u>Surgical System and Operational Activities</u>



The UW robot was initially assembled in a controlled environment (air conditioned office building) on the first day. It was then disassembled, packed in protective containers and driven over rough terrain to open range with very little vegetation – prairie grass was predominate with very few deciduous tress. The robot and control stations were assembled, used and disassemble three times in three different locations. The environment was characterized by temperatures exceeding 100°F, dry, arid, dusty, and windy. In addition to communications, all resources had to be brought in, including water and electrical power.

The robot was mounted on rails along side a portable pseudo operating table. The inanimate arms were secured to the table rails. The table and control boxes were set up under a tent. The master controller and other ancillary equipment were set in a second tent about 100 feet away from the robot. The gasoline-powered generators were positioned behind the vehicles to minimize noise and odor.

The surgical robot comes with two video views (1) a surgical camera and (2) an overview camera. Each camera captured and recorded video independently. Only the surgical camera view was sent to the remote via the digital data link to limit bandwidth utilization. The control software has built into it, the ability to record all joint and motor positions.

UW's TCP/IP networking requirements (bandwidth and port usage) for the robot controls included two primary and two secondary communication channels. The "primary" communication required was video and teleoperation data, which used most of the bandwidth. In addition, we intermittently used remote computer login via SSH and/or SFTP, and a teleconferencing/chat channel for communication between locations. The secondary channels did not add significant bandwidth requirements. Teleoperation used a single bi-directional UDP port sending 2000, 40 byte (640 bit) packets per second (1,000 each way), about 640 Kbps.

Video used three UDP streams with bandwidth scalable (tradeoff quality for bandwidth) in the range of 100-500 kbps at a minimum. Based on an estimated bandwidth of 1.2 Mbps, it was necessary to send a single video stream to optimize the quality of the operative video image provided to the remote surgeon. (Due to the classified nature of the Puma DDL, AeroVironment could not disclose communication details or allow third party tools to sniff the network.)

The master controllers that manipulate the robotic arms are SensAble Phantom Omnis. Using the HaiVision CODEC and these Omnis, the surgeons were able to successfully control the remote robotic slave arms over the Puma DDL. .

<u>Surgical procedures</u>

Two surgeons from UC, Dr. Timothy Broderick and Dr. Lynn Huffman took turns at the surgeon's console manipulating surgical arms. Using a video image and the Phantom Omni controllers, they moved the tools along specific paths in space and positioned their tips at predetermined spots on the latex objects. They were able to simulate various maneuvers that surgeons normally perform. Suturing was difficult as the kinematic control of the prototype robot requires additional

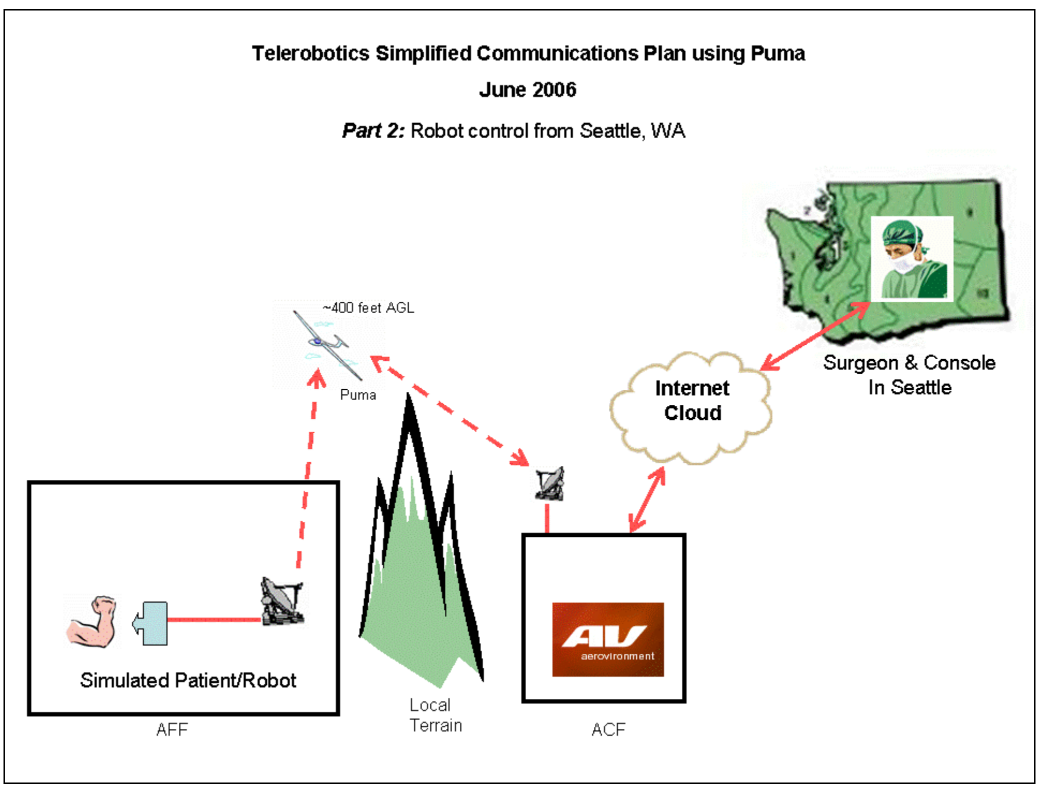
refinement. Refinement of kinematic control and robot packet transfer protocol to minimize bandwidth utilization will be performed during the no cost extension period. During the experiment, signal transmission delays were 20 milliseconds (ms) and CODEC delays were 180 ms. While the total latency of 200 ms was noticeable by the surgeons, it did not substantially interfere with their control of the robot. The surgical experiments were designed to measure various aspects of performance.

Integration of a high performance CODEC

The videoconferencing segment was implemented through a partnership with HaiVision. They provided their Hai560 high-end videoconferencing CODEC (http://www.haivision.com/products/hai500/). The Hai560 used its two video channels to simulate stereoscopic vision, this time the views will be a monoscopic surgical view and an overhead view (described earlier). A third channel provided the audio.

Linkage from Simi Valley to Seattle

Once the tests were successful in Simi Valley, Dr. Broderick and Dr. Hannaford traveled to Seattle. On the last day, the robot and Puma were deployed in the field at Simi Valley. The controllers were in Seattle. The network between Seattle and the experimental test site was established. Video linkage was established and Seattle could see the robot and the activities in Simi Valley. The robot however, could not be manipulated. During configuration on Friday morning the server that controlled the robot suffered a catastrophic and unrecoverable hardware failure (motherboard malfunction).



REPORTABLE OUTCOMES

Initial HAPsMRT experiments were very successful. This activity is the first time ever that a UAV and a surgical robot were deployed in an extreme environment and effectively used. These tests demonstrated that the Puma, which is normally used for military activities, could be adapted as a communications platform to transmit images and instrument controls of a surgical robot. This was the first time a surgical robot was manipulated wirelessly using a UAV. This activity also demonstrated that robotic instrument controls could be transmitted using a wireless (802.11g) system as a redundancy. In the upcoming year (during the no cost extension), additional experiments are planned to further improve and validate function of the mobile robotic telesurgery system.

Reports

A summary of this project was presented at a TATRC product line review (PLR) conducted in June 2006. In addition, several manuscripts and abstracts have been prepared. These include:

Manuscripts

1. Lum MH, Friedman DCW, King HH, Broderick T, Sinanan MN, Rosen J, Hannaford B. Field Operation of a Surgical Robot via Airborne Wireless Radio Link. Submitted, Proceedings of IEEE Int. Conf. on Robotics and Automation, ICRA2007, Rome Italy, 2007.
2. Rosen J, Hannaford, B. Doc at a Distance. IEEE Spectrum, pp. 34-39, October 2006.

Abstracts

1. Harnett BM Broderick TJ, Doarn CR, Huffman L, Rosen J, Hannaford B. Small Unmanned Aerial Vehicle as a Network Access Point for Tele-Robotic Surgical Intervention in the Battlefield. Medicine Meets Virtual Reality 14. Long Beach, CA. February 2007.
2. Doarn CR, Harnett BM, Broderick TJ. Telesurgery: What are the Possibilities? 12th Annual Meeting and Exposition of the American Telemedicine Association, Nashville, TN. May 2007. *Submitted.*
3. Doarn CR, Harnett BM, Broderick TJ. Telesurgery: The Convergence of Telecommunications, Informatics and Robotics. HIMSS, Panel Presentation. New Orleans, LA. February 2007.
4. Hoffman L, Doarn CR, Harnett B, Moses G, Broderick TJ. Recent Advances in Robotic Telesurgery and Applications to Battlefield Trauma. 2nd Annual Meeting of the Association of Academic Surgeons. Phoenix, AZ. February 2007. *Submitted*
5. Doarn CR and Broderick TJ, Emerging Telecommunications for Telesurgical Applications. Immersive Medical Telepresence - Internet -2. Barrow Neurological

Institute, St. Joseph’s Hospital and Medical Center, Phoenix, AZ. September 2006.

Contracted Deliverables

AeroVironment:

Aerovironment provide the communications platforms including a LAN/WLAN at their facilities, the UAV as a routing platform, downlink and routing to the commercial Internet at a rate no less than 2 Mbps end-to-end. In addition, AeroVironment provided site accommodations for the experiment, safe haven for equipment in off-hours, staging location, secure room for the surgeon console (RCC), transportation logistics, engineering and support.

HaiVision

HaiVision provided the CODECs for videoconferencing capability including bidirectional video (two channels) and audio from the in the field and from the field to the commercial Internet and onto UW as well as any application-specific performance data.

University of Washington

UW provided their prototype surgical robotic platform. This robot was deployed in Simi Valley. It was set up and taken down everyday in extreme environmental conditions including blowing dust and temperatures exceeding 100°F.

University of Cincinnati

UC was the recipient of the TATRC grant. They provided project administration, technical support and most important surgical expertise.

CONCLUSION

This proposed effort, complimented by the multidisciplinary team of collaborators, will provide a strong foundation of expertise that will be available to the military as well as NASA as it meets its exploration initiatives. MRT is feasible and holds great promise of improving medical care by allowing a remote surgeon to effectively operate on an injured soldier regardless of the soldier’s location or environment. This project will deliver a robust MRT system with performance that has been validated in an extreme environment. This project brings together the necessary military, surgical, robotic and telecommunications partners to provide the eclectic technology and expertise that will bring mobile robotic telesurgical care of soldiers closer to reality.

Next Steps

There are several next steps that will take place in the coming year. These include the following.

1) The next phase of these experiments could further evaluate HAPsMRT by piggybacking on the flight test of a High Altitude Long Endurance (HALE) UAV from AeroVironment named Global Observer. These experiments are tentatively schedule to occur in Kauai, HI at the Pacific Missile Range Facility or Yuma, AZ within the next 12 months.
2) The robot, located in Seattle will be controlled by surgeons at UC to conduct a series experiments targeted at improving robotic kinematic control and communication protocols. Surgical, robotic and network performance will be characterized to facilitate future mobile robotic telesurgery. UC has procured SensAble Omnis and software to remotely control the robot in Seattle. The network linkage will be default Internet and Internet2.
3) Provide interactive surgeon use and feedback to make robot kinematic control more intuitive.
4) Improve communication protocol to limit bandwidth used for robot control (e.g. dynamically adjust packet transmission based upon master control movement).

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APPENDICES

None provided.

Addendum 1
Acronym / Symbol Definition

AGL	Above Ground Level
ARC	Ames Research Center
BMIST	Battlefield Medical Information System-Tactical
CODEC	Coder / Decoder
CPOD	Crew Physiological Operation Device
CSI	Center for Surgical Innovation
DARPA	Defense Advanced Research Projects Agency
ELAN	Extended Local Area Network
FDDMTF	Forward Deployable Digital Medical Treatment Facility
GEO	Geostationary Earth Orbit
GGTS	Global Grid Telemedicine System
HAPs	High Altitude Platforms
IP	Internet Protocol
Kbps	Kilo bits per second
LEO	Low Earth Orbit
MAMC	Madigan Army Medical Center
MEO	Mid Earth Orbit
MIM	Mission Information Management
Mbps	Mega bits per second
MOR	Mobile Operating Room
MRT	Mobile Robotic Surgery
NASA	National Aeronautics and Space Administration
NEEMO	NASA Extreme Environments Mission Operations
NIH	National Institutes of Health
NSSA	National Security Space Architecture
PMRF	Pacific Missile Range Facility
RCC	Remote Command Center
TATRC	Telemedicine and Advanced Technology Research Center

TCP	Transfer Control Protocol
UAF	Unmanned Airborne Vehicle
UC	University of Cincinnati
UDP	User Datagram Protocol